

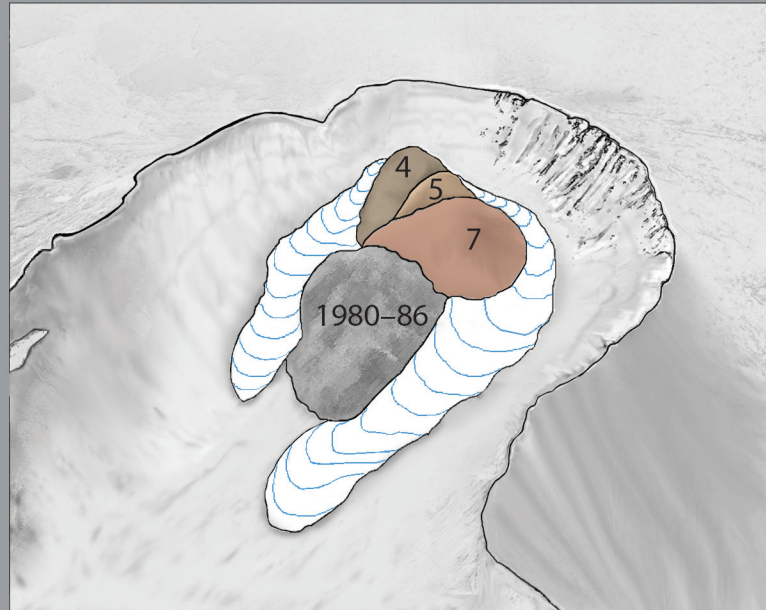
A Volcano Rekindled: the Renewed Eruption of Mount St. Helens, 2004–2006

Professional Paper 1750

U.S. Department of the Interior
U.S. Geological Survey

COVER

Mount St. Helens crater and new dome, September 12, 2006. Oblique aerial view from the north. Crater rim is about 2 km across. Spines 4, 5, and 7 of the new dome (see labeled sketch below) form conical masses that have nearly or completely buried other spines of the eruptive sequence. At slightly lower altitude, Crater Glacier's east and west arms nestle the craggy 1980–86 dome as they plunge northward from the crater floor.



A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006

Edited by David R. Sherrod, William E. Scott, and Peter H. Stauffer

Professional Paper 1750

**U.S. Department of the Interior
U.S. Geological Survey**

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

This report and any updates to it are available online at:
<http://pubs.usgs.gov/pp/1750/>

For product and ordering information:
World Wide Web: <http://www.usgs.gov/pubprod>
Telephone: 1-888-ASK-USGS (1-888-275-8747)

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment:
World Wide Web: <http://www.usgs.gov>
Telephone: 1-888-ASK-USGS (1-888-275-8747)

Any use of trade, product, or firm names is for descriptive purposes only and does not imply
endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to
reproduce any copyrighted material contained within this report.

Suggested citation:
Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., 2008, A volcano rekindled; the renewed eruption of Mount St. Helens,
2004-2006: U.S. Geological Survey Professional Paper 1750, 856 p. and DVD-ROM.

Cataloging-in-publication data are on file with the Library of Congress (<http://www.loc.gov/>).

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, August 27, 2008
Text edited by Peter H. Stauffer, Tracey L. Suzuki,
James W. Hendley II, and George A. Havach
Layout by Judy Weathers and Susan Mayfield

Foreword

Late September and early October 2004 saw intense seismic unrest, rapid ground deformation, and explosions heralding the renewal of lava-dome growth in the crater of Mount St. Helens, Washington. Thus ended the relative calm of two decades since the renowned 1980–86 eruptions. Memories of the May 18, 1980, tragedy and its aftermath prompted a high level of concern among the public, public officials, and the media. Response to this unrest and eruption was led by scientists at the U.S. Geological Survey's (USGS) David A. Johnston Cascades Volcano Observatory (CVO). Established following the 1980 eruption, CVO was named for the spirited young USGS volcanologist who lost his life during the initial minutes of the May 18 cataclysm. USGS scientists worked in close cooperation with CVO's long-time partner in monitoring the volcanoes of Washington and Oregon, the Pacific Northwest Seismic Network at the University of Washington. This cooperation ensured that local land and emergency managers, public officials, key government agencies, media representatives, and the public received the information needed to protect life and property, as well as to appreciate the spectacle of an erupting volcano. USGS scientists from sister volcano observatories—Alaska, Hawaiian, Long Valley, and Yellowstone—and the broader USGS community contributed significantly to the effort. USGS scientists relied on lessons learned from responding to previous volcanic crises in the United States and abroad. Scientists from more than a dozen academic institutions undertook valuable scientific studies of the eruption. New instrumentation from the National Science Foundation-sponsored Plate Boundary Observatory aided in geodetic monitoring. The response was bolstered by vast improvements in monitoring technology, information management, and understanding of volcanic processes that were spawned by the 1980 eruption and other eruptions during the late 20th century.

The USGS is proud to have cooperated closely with the Gifford Pinchot National Forest, home of the Mount St. Helens National Volcanic Monument, the Washington State Emergency Management Division, county emergency-management agencies, the National Weather Service, the Federal Aviation Administration, and the Federal Emergency Management Agency in fulfilling its mandated role under the Disaster Relief Act of 1974 (P.L.93–288) “to provide technical assistance to State and local governments to ensure timely and effective disaster warning is provided.” This multichaptered Professional Paper, released as the most recent period of the Mount St. Helens lava-dome building ends after nearly three and one-half years of continuous activity, adds to our understanding of how volcanic systems work, and how scientists must work together with a broad array of agencies and public officials to mitigate risk from volcanic activity.

Occurring more than a quarter century ago, the catastrophic 1980 eruption of Mount St. Helens may seem to some as just a historical footnote. This Professional Paper documenting both the volcano's recent activity and the need for coordinated warning and disaster response should serve the public well as a reminder of the challenges and consequences of living near an active volcano. Previous USGS Director Dallas Peck said it best: “The lessons of Mount St. Helens must not—and will not—be forgotten.”

Mark D. Myers
Director,
U.S. Geological Survey

Anthony I. Qamar, 1943–2005

Research Assistant Professor, University of Washington
Co-Principal Investigator, Pacific Northwest Seismic Network
Washington State Seismologist, 1988–2005

Anthony “Tony” Qamar was a highly regarded, generous scientist whose career encompassed the Mount St. Helens eruptions of 1980–86 and 2004 (ongoing at this writing, June 2007). Tony and his colleague, Dan Johnson, were killed in a tragic auto accident October 4, 2005, while traveling to Washington’s Olympic Peninsula to retrieve a GPS receiver.

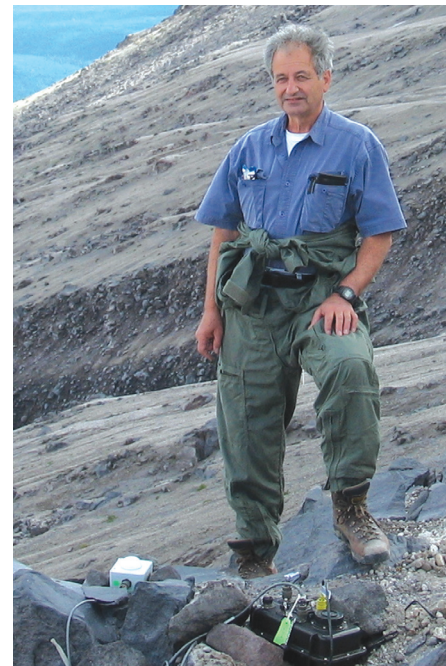
Tony loved mountains, particularly volcanoes. Unbeknownst to many colleagues, Tony was an accomplished climber with major first ascents to his credit. He often combined his professional world with his love of the outdoors by accepting the task of repairing remote and inaccessible seismographs, such as those high on Mount Rainier and Glacier Peak. In 1980 he was one of the first scientists to appear at Mount St. Helens in response to precursory seismicity. Camping in the snow with a portable seismograph and thermal infrared imager, he witnessed and recorded many of the early phreatic eruptions.

In September 2004, Tony again became immersed in volcano seismology as Mount St. Helens reawakened. Moving from his regular office, he set up “camp” in a small, cramped room across from the seismology lab, where he was a resource for the staff and seismology students at the University of Washington’s Department of Earth and Space Sciences and also for news media who used the lab during the early chaotic months of the eruption. He developed several automated computer codes (in FORTRAN) that enabled the staff of the Cascades Volcano Observatory and the Pacific Northwest Seismic Network to make sense of the overwhelming number of earthquakes and to track changes in real time. The paper on which he is first author in this volume (chap. 3) is based on these computational efforts and is, we hope, close to the paper he intended to write.

While fundamentally a seismologist interested in the stresses that trigger earthquakes, Tony let his curiosity drive

his research in diverse directions. He published papers on the seismic structure of the Earth’s inner core, seismic signals generated by meteors or the space shuttle, ice quakes from glaciers recorded by high-frequency seismographs, and the slowly straining tectonic plates as detected by GPS receivers.

Tony was an excellent classroom teacher and even better mentor. As a research collaborator he was generous with his time and ideas, interested more in working with others to achieve a better understanding of a scientific problem than in claiming his piece of the intellectual pie through first-author publications. Those around him were enriched by his presence, knowing he was a friend first and professor second. Students frequently approached him with questions, both technical and personal, and they always left with their answers in hand and their egos intact. The hole left by his passing is both wide and deep.



Tony Qamar poses near seismic equipment he helped to install on the flanks of Mount St. Helens in the summer of 2005

Contributors to This Professional Paper

Cascades Volcano Observatory

Beeler, Nick M.
 Couchman, Marvin R.
 Denlinger, Roger P.
 Doukas, Michael P.
 Driedger, Caroyl L.
 Dzurisin, Daniel
 Endo, Elliot T.
 Gardner, Cynthia A.
 Gerlach, Terrence M.
 Gooding, Daniel J.
 Iverson, Richard M.
 Iwatsubo, Eugene Y.
 Janda, Christine G.
 Kingsbury, Cole G.
 LaHusen, Richard G.
 Lisowski, Michael
 Lockhart, Andrew B.
 Logan, Matthew
 Lu, Zhong
 Major, Jon J.
 Mastin, Larry G.
 McGee, Kenneth A.
 Moran, Seth C.
 Pallister, John S.
 Roeloffs, Evelyn
 Schilling, Steve P.
 Scott, William E.
 Sherrod, David R.
 Spicer, Kurt R.
 Swinford, Kelly J.
 Thornber, Carl R.
 Vallance, James W.
 Walder, Joseph S.
 Wolfe, Edward W.
 U.S. Geological Survey
 1300 SE Cardinal Court
 Vancouver, WA 98683

Menlo Park

Bergfeld, Deborah
 Calvert, Andrew T.
 Clynne, Michael A.
 Evans, William C.
 Evarts, Russell C.
 Fleck, Robert J.
 Lanphere, Marvin A.
 U.S. Geological Survey
 345 Middlefield Road
 Menlo Park, CA 94025

Denver

Brownfield, Isabelle K.
 Lowers, Heather A.
 Meeker, Gregory P.
 Messerich, James A.
 Thompson, Ren A.
 U.S. Geological Survey
 Denver Federal Center
 Denver, CO 80225

Alaska Volcano Observatory

Neal, Christina A.
 Schneider, David J.
 Wessels, Rick L.
 U.S. Geological Survey
 4200 University Drive
 Anchorage, AK 99508

Hawaiian Volcano Observatory

Poland, Michael P.
 U.S. Geological Survey
 PO Box 51
 Hawaii National Park, HI 96718

University of Washington

Creager, Kenneth C.
 Crosson, Robert S.
 Donnelly, Carrie T.
 Malone, Stephen D.
 McChesney, Patrick J.
 Norris, Robert D., USGS
 Qamar, Anthony I. *
 Steele, William P.
 Thelen, Weston A.
 Wright, Amy K.
 Earth and Space Sciences
 Box 351310
 Seattle, WA 98195

U.S. Department of Agriculture, Forest Service

Frenzen, Peter M.
 Knappenberger, Thomas H.
 Lapcewich, Dennis
 Matarrese, Michael T.
 Gifford Pinchot National Forest
 10600 N.E. 51st Circle
 Vancouver, WA 98682

Brown University

Devine, Joseph D., III
 Rutherford, Malcolm J.
 Department of Geological Sciences
 324 Brook Street
 Providence, RI 02912

Iowa State University

Iverson, Neal R.
 Moore, Peter L.
 Department of Geological and
 Atmospheric Sciences
 Ames, IA 50011

McGill University

Berlo, Kim
 Earth & Planetary Sciences,
 McGill University
 3450 University St.
 Montreal, Quebec, Canada
 H3A 2A7

Oregon State University

Kent, Adam J.R.
 Department of Geosciences, OSU
 Wilkinson Hall
 Corvallis, OR 97331

Portland State University

Broderick, Cindy A.
 Streck, Martin J.
 Department of Geology, PSU
 PO Box 751
 Portland, OR 97207

Southern Methodist University

Quick, James E.
 Office of Research and Graduate
 Studies
 P.O. Box 750240
 Dallas, TX 75275-0240

University of Bristol

Blundy, Jon
 Department of Earth Sciences
 Wills Memorial Building
 Bristol BS8 1RJ, UK

* Deceased

University of California

Cooper, Kari M.
 Geology Department, UC Davis
 One Shields Avenue
 Davis, CA 95616
 Herriott, Trystan M.
 Department of Earth Science,
 UC Santa Barbara
 Webb Hall, Building 526
 Santa Barbara, CA 93106

University of Cambridge

Edmonds, Marie
 Downing Street
 Cambridge CB2 3EQ, UK

University of Iowa

Reagan, Mark K.
 Rowe, Michael C.
 Wortel, Matthew
 Department of Geoscience
 121 Trowbridge Hall
 Iowa City, IA 52242

University of Memphis

Horton, Stephen P.
 Center for Earthquake Research
 and Information
 3890 Central Ave
 Memphis, TN 38152

University of Pittsburgh

Ramsey, Michael S.
 Department of Geology &
 Planetary Science
 200 SRCC Building
 Pittsburgh, PA 15260

University of Oregon

Cashman, Katharine V.
 Department of Geological Sciences,
 UO
 1272 University of Oregon
 Eugene, OR 97403

Western Washington University

Caplan-Auerbach, Jacqueline
 Geology Department, WWU
 516 High Street
 Bellingham, WA 98225

Clark County

Needham, Deborah H.
 Clark Regional Emergency Services
 Agency
 710 W 13th St.
 Vancouver, WA 98660

American Museum of Natural History

Mandeville, Charles W.
 American Museum of
 Natural History
 Central Park West at 79th Street
 New York, NY 10024

Washington Military Department

Harper, Robert B.
 Emergency Management Division
 Building 20
 Camp Murray, WA 98430

Contents

Foreword	iii
Anthony I. Qamar, 1943–2005	iv
Contributors to This Professional Paper	v

Chapters

Overview

1 Overview of the 2004 to 2006, and continuing, eruption of Mount St. Helens, Washington	3
By W.E. Scott, D.R. Sherrod, and C.A. Gardner	

Seismicity of the eruption

2 Seismicity associated with renewed dome building at Mount St. Helens, 2004–2005.....	27
By S.C. Moran, S.D. Malone, A.I. Qamar, W.A. Thelen, A.K. Wright, and J. Caplan-Auerbach	
3 Near-real-time information products for Mount St. Helens—tracking the ongoing eruption	61
By A.I. Qamar, S.D. Malone, S.C. Moran, W.P. Steele, and W.A. Thelen	
4 Absolute and relative locations of earthquakes at Mount St. Helens, Washington, using continuous data: implications for magmatic processes.....	71
By W.A. Thelen, R.S. Crosson, and K.C. Creager	
5 Broadband characteristics of earthquakes recorded during a dome-building eruption at Mount St. Helens, Washington, between October 2004 and May 2005	97
By S.P. Horton, R.D. Norris, and S.C. Moran	
6 Seismicity and infrasound associated with explosions at Mount St. Helens, 2004–2005..	111
By S.C. Moran, P.J. McChesney, and A.B. Lockhart	
7 Seismic-monitoring changes and the remote deployment of seismic stations (seismic spider) at Mount St. Helens, 2004–2005	129
By P.J. McChesney, M.R. Couchman, S.C. Moran, A.B. Lockhart, K.J. Swinford, and R.G. LaHusen	

Geological observations of lava-dome growth

8 Use of digital aerophotogrammetry to determine rates of lava dome growth, Mount St. Helens, Washington, 2004–2005.....	145
By S.P. Schilling, R.A. Thompson, J.A. Messerich, and E.Y. Iwatsubo	
9 Growth of the 2004–2006 lava-dome complex at Mount St. Helens, Washington.....	169
By J.W. Vallance, D.J. Schneider, and S.P. Schilling	
10 Photogeologic maps of the 2004–2005 Mount St. Helens eruption	209
By T.M. Herriott, D.R. Sherrod, J.S. Pallister, and J.W. Vallance	

- 11 Remote camera observations of lava dome growth at Mount St. Helens, Washington, October 2004 to February 2006..... 225
By M.P. Poland, D. Dzurisin, R.G. LaHusen, J.J. Major, D. Lapcewich, E.T. Endo, D.J. Gooding, S.P. Schilling, and C.G. Janda
- 12 Extrusion rate of the Mount St. Helens lava dome estimated from terrestrial imagery, November 2004–December 2005 237
By J.J. Major, C.G. Kingsbury, M.P. Poland, and R.G. LaHusen
- 13 Effects of lava-dome growth on the Crater Glacier of Mount St. Helens, Washington.... 257
By J.S. Walder, S.P. Schilling, J.W. Vallance, and R.G. LaHusen

Geodesy and remote sensing

- 14 Constraints and conundrums resulting from ground-deformation measurements made during the 2004–2005 dome-building eruption of Mount St. Helens, Washington 281
By D. Dzurisin, M. Lisowski, M.P. Poland, D.R. Sherrod, and R.G. LaHusen.
- 15 Analysis of GPS-measured deformation associated with the 2004–2006 dome-building eruption of Mount St. Helens, Washington..... 301
By M. Lisowski, D. Dzurisin, R.P. Denlinger, and E.Y. Iwatsubo
- 16 Instrumentation in remote and dangerous settings; examples using data from GPS “spider” deployments during the 2004–2005 eruption of Mount St. Helens, Washington..335
By R.G. LaHusen, K.J. Swinford, M. Logan, and M. Lisowski
- 17 Use of thermal infrared imaging for monitoring renewed dome growth at Mount St. Helens, 2004347
By D.J. Schneider, J.W. Vallance, R.L. Wessels, M. Logan, and M.S. Ramsey
- 18 Radar interferometry observations of surface displacements during pre- and coeruptive periods at Mount St. Helens, Washington, 1992–2005..... 361
By M.P. Poland and Z. Lu

Models and mechanics of eruptive processes

- 19 From dome to dust: shallow crystallization and fragmentation of conduit magma during the 2004–2006 dome extrusion of Mount St. Helens, Washington 387
By K.V. Cashman, C.R. Thornber, and J.S. Pallister
- 20 Frictional properties of the Mount St. Helens gouge 415
By P.L. Moore, N.R. Iverson, and R.M. Iverson
- 21 Dynamics of seismogenic volcanic extrusion resisted by a solid surface plug, Mount St. Helens, 2004–2005..... 425
By R.M. Iverson
- 22 Constraints on the size, overpressure, and volatile content of the Mount St. Helens magma system from geodetic and dome-growth measurements during the 2004–2006+ eruption 461
By L.G. Mastin, E. Roeloffs, N.M. Beeler, and J.E. Quick

Crisis management

- 23 Managing public and media response to a reawakening volcano: lessons from the 2004 eruptive activity of Mount St. Helens..... 493
By P.M. Frenzen and M.T. Matarrese
- 24 Hazard information management during the autumn 2004 reawakening of Mount St. Helens volcano, Washington..... 505
By C.L. Driedger, C.A. Neal, T.H. Knappenberger, D.H. Needham, R.B. Harper, and W.P. Steele

Volcanic emissions

- 25 Pre- and post-eruptive investigations of gas and water samples from Mount St. Helens, Washington, 2002 to 2005 523
By D. Bergfeld, W.C. Evans, K.A. McGee, and K.R. Spicer
- 26 Emission rates of CO₂, SO₂, and H₂S, scrubbing, and preeruption excess volatiles at Mount St. Helens, 2004–2005 543
By T.M. Gerlach, K.A. McGee, and M.P. Doukas
- 27 Chlorine degassing during the lava dome-building eruption of Mount St. Helens, 2004–2005 573
By M. Edmonds, K.A. McGee, and M.P. Doukas

Petrologic and geochemical investigations of eruptive products


- 28 The Pleistocene eruptive history of Mount St. Helens, Washington, from 300,000 to 12,800 years before present..... 593
By M.A. Clyne, A.T. Calvert, E.W. Wolfe, R.C. Evarts, R.J. Fleck, and M.A. Lanphere
- 29 Identification and evolution of the juvenile component in 2004–2005 Mount St. Helens ash..... 629
By M.C. Rowe, C.R. Thornber, and A.J.R. Kent
- 30 Petrology of the 2004–2006 Mount St. Helens lava dome—implications for magmatic plumbing and eruption triggering..... 647
By J.S. Pallister, C.R. Thornber, K.V. Cashman, M.A. Clyne, H.A. Lowers, C.W. Mandeville, I.K. Brownfield, and G.P. Meeker,
- 31 Magmatic conditions and processes in the storage zone of the 2004–2006 Mount St. Helens dacite 703
By M.J. Rutherford and J.D. Devine, III
- 32 Chemistry, mineralogy, and petrology of amphibole in Mount St. Helens 2004–2006 dacite 727
By C.R. Thornber, J.S. Pallister, H.A. Lowers, M.C. Rowe, C.W. Mandeville, and G.P. Meeker
- 33 Evolving magma storage conditions beneath Mount St. Helens inferred from chemical variations in melt inclusions from the 1980–1986 and current (2004–2006) eruptions..... 755
By J. Blundy, K.V. Cashman, and K. Berlo

34	Plagioclase populations and zoning in dacite of the 2004–2005 Mount St. Helens eruption: constraints for magma origin and dynamics.....	791
	By M.J. Streck, C.A. Broderick, C.R. Thornber, M.A. Clynne, and J.S. Pallister	
35	Trace element and Pb isotope composition of plagioclase from dome samples from the 2004–2005 eruption of Mount St Helens, Washington	809
	By A.J.R. Kent, M.C. Rowe, C.R. Thornber, and J.S. Pallister	
36	^{238}U - ^{230}Th - ^{226}Ra disequilibria in dacite and plagioclase from the 2004–2005 eruption of Mount St. Helens	827
	By K.M. Cooper and C.T. Donnelly	
37	Timing of degassing and plagioclase growth in lavas erupted from Mount St. Helens, 2004–2005, from ^{210}Po - ^{210}Pb - ^{226}Ra disequilibria.....	847
	By M.K. Reagan, K.M. Cooper, J.S. Pallister, C.R. Thornber, and M. Wortel	

In pocket at back:

DVD-ROM containing the entire book, including digital appendixes to various chapters.

This page intentionally left blank



Late September and early October 2004 saw intense seismic unrest, rapid ground deformation, and explosions heralding the renewal of lava-dome growth in the crater of Mount St. Helens, Washington. Thus ended the relative calm of two decades since the renowned 1980–86 eruptions. . . . Occurring more than a quarter century ago, the catastrophic 1980 eruption of Mount St. Helens may seem to some as just a historical footnote. This Professional Paper documenting both the volcano’s recent activity and the need for coordinated warning and disaster response should serve the public well as a reminder of the challenges and consequences of living near an active volcano.

From the Foreword by Mark D. Myers